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Determining Plasma Potential from RF Measurements Using an Impedance Probe

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Determining plasma potential from rf measurements using an impedance probe

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Abstract

We present an rf technique for finding plasma potential for both low and high neutral pressure plasmas in the thin sheath limit. It requires only readily available instrumentation and has the added advantage that the measurement is non-perturbative to the plasma. The technique is based on combined experimental and theoretical methods developed in the Charged Particle Physics Branch at the Naval Research Laboratory. The method has general application to diverse areas of plasma investigations in the laboratory or in space plasma measurement application. It can be used with *in situ* instrumentation itself and can be extended to provide an estimate of the sheath structure for arbitrarily shaped surfaces. Because the magnitude of the applied signal used is much smaller in magnitude than typical applied dc potentials, it is transparent to the existing plasma/probe interface.

1. Introduction

Although almost a century old, the most widely used technique to present day^{1,2} for determining local plasma electron parameters relies on measuring the impedance of a small probe, usually a cylinder or a sphere, placed in the plasma. Since analysis relies on measurement of the dc impedance of the sheath region, various models^{3,4,5}, and in some cases experiments⁶, have been used to estimate the electron density structure of the sheath and pre-sheath regions formed. The conventional Langmuir probe^{7,8} provides the means for determining the electron density, temperature, plasma potential and the electron energy distribution function from the current-voltage curve.^{4,9,10} In most applications it is assumed that the distribution is Maxwellian. In addition to non-Maxwellian velocity distributions⁵, there are various other complicating factors to these analyses including secondary electron emission, ion collisions, contaminants on the probe surface, negative ions, and plasma production and decay within the sheath. Also highly collisional plasmas further undermine common assumptions as to ion velocity at the sheath edge and complicate standard techniques which rely on solution of the Poisson equation.

The use of rf impedance probes eliminates many of the drawbacks outlined above. Although impedance probe techniques for determining electron density are not new, determinations of electron temperature, plasma potential and the electron distribution

function typically depend on the use of additional conventional Langmuir probes and associated analysis.

In earlier works using rf techniques with plasma probes in laboratory experiments we have demonstrated the existence of collisionless resistance in the sheath of a spherical probe¹¹, shown that this leads to a method of finding the electron sheath density profile¹², and proposed a method of measuring electron temperature using the rf results¹³. Most recently we have been able to determine plasma potential from these measurements. In addition the electron distribution function becomes accessible requiring only a single derivative of the inverse ac resistance as opposed to the usual convention which requires a 2nd derivative of collected current with respect to applied voltage bias. We treat this issue in a subsequent paper.

Plasma potential ϕ_p is most often determined in principle by noting that the rise in probe collected current with probe voltage V_p falls rapidly above ϕ_p . Therefore dI_p/dV_p has a peak and

$$\frac{d^2 I_p}{dV_p^2} = 0 \quad (1)$$

at ϕ_p . A number of authors¹⁴ claim this method gives ϕ_p unequivocally. However even small amounts of noise can produce large fluctuations in the derivatives (particularly of 2nd order) and those fluctuations generate uncertainty in ϕ_p . Many authors resort to fitting routines of various forms which can be based on the probe geometry to determine this inflection point. Because of the limitations in these historical methods of finding ϕ_p the ability to lessen the effects of noise in this determination is of prime importance. In the method outlined in this paper, ϕ_p determination relies on a local minimum of the ac resistance (which at plasma potential is equal to the real part, $\text{Re}Z$, of the complex plasma impedance since there is no sheath) and therefore only a first derivative.

II. Description of Experimental Procedure

We briefly describe here the experimental basis for our measurements leaving further description in references to earlier works cited below for the interested reader.

All of the experiments described took place in the Space Physics experimental facility at the Naval Research Laboratory which is pictured shown in Figure 1. The larger portion of the cylindrical chamber where these experiments took place is seen toward the rear of the figure surrounded by 5 large magnetic field coils and has a diameter of 2 m and length 5 m. Argon plasma densities in this work varied in the range of 10^7 to 10^9 cm^{-3} . Typical chamber pressure was 1×10^{-4} Torr. Typical electron-neutral collision frequencies for these plasmas are near $\nu_{en} \sim 6 \times 10^5 \text{ s}^{-1}$ which is much less than the plasma frequency, $\omega_{p0} \sim 6 \times 10^8 \text{ s}^{-1}$ ($f_{p0} \sim 100 \text{ MHz}$). Neutrals and ions are at room temperature. The plasma is created by a tungsten filament source biased to -70 Volts and covering a large portion of the inner end-plate surface area. A low-level axial magnetic field on the order of 1-2 Gauss is provided by the 5 circular water-cooled magnetic field coils aligned axially in a Helmholtz configuration; magnetic field strengths near 1 kG are

available for other experimental programs. Electron density and temperature measurements are taken with a dc swept cylindrical Langmuir probe which is constantly heated to prevent contamination buildup¹⁵ or with an emissive probe. Also the spheres under investigation were swept as Langmuir probes for comparison. Further details of this experimental configuration, and for the laboratory configuration in general are found elsewhere.¹⁶

Three small stainless steel spheres of 9.5 mm, 12.5 mm and 25.4 mm radius were connected to an HP8735D Network Analyzer through 50 Ω coaxial cable for the data presented in this work. This arrangement with the analyzer and the coupling circuitry is shown schematically in Figure 2. The spheres were mounted on a 1/4 inch diameter ceramic and steel support which is connected to 1/4 inch diameter semi-rigid copper 50 Ohm coaxial cable.

For all of the experiments, the determination of plasma impedance depends upon the network analyzer measurement of the complex reflection coefficient, $\Gamma(\omega)$. From this measurement the analyzer returns as separate outputs $Re Z_{ac}(\omega)$ and $Im Z_{ac}(\omega)$ where,

$$Z_{ac}(\omega) = Z_0 \left[\frac{1 + \Gamma(\omega)}{1 - \Gamma(\omega)} \right] \quad (2)$$

and Z_0 ($=50 \Omega$) is the internal impedance of the analyzer. We also note that the ratio of reflected-to-total power is given by,

$$|\Gamma|^2 = \frac{P_r}{P_0} \quad (3)$$

where $P_0 = P_R + P_T$ with P_R and P_T the reflected and transmitted powers, respectively. (The quantity $1 - |\Gamma|^2$ is the normalized transmitted power and this output is also available). The impedance from the cabling and support is compensated through instrument calibration when connected to a 50 Ω resistor or when calibrated as an open, or short, circuit. An open circuit corresponds then to $\Gamma=1$, a short circuit to $\Gamma=-1$ and if the load impedance is a perfect match, $\Gamma=0$. As the change in the complex reflection coefficient for the sphere in the plasma is very small, this calibration is a critical step. Care must be taken to avoid unwanted rf noise or reflections from the chamber walls or other nearby probes. The method is tested by connecting other known resistances and capacitances to the end of the probe shaft to ensure that any error is much smaller than the changes in the impedance we wish to measure.

III. Determining ϕ_p

III.a Theory

We have shown elsewhere¹¹ that in the absence of any sheath inductance the relation between the measured $Re(Z)$ and the ac resistance R_{ac} is given by,

$$Re(Z_{ac}) = \frac{R_{ac}}{1 + (\omega R_{ac} C_s)^2} \quad (4)$$

where,

$$R_{ac} = \left(\frac{dI_e}{dV_p}\right)^{-1} = \frac{1}{4\pi\epsilon_0} \left(\frac{\lambda_D}{r_0}\right)^2 e^{-eV_0/T_e} \sqrt{\frac{2\pi m_e}{T_e}} \quad (5)$$

and we require that $\omega_{pi} < \omega < \omega_{pe}(r_0)$ with $\omega_{pe}(r_0)$ the electron plasma frequency at the probe surface, r_0 . V_p is taken as the dc bias with respect to plasma potential, C_s is sheath capacitance, λ_D is Debye length, and m_e , T_e are electron mass and temperature, respectively. These equations arise from a combination of physical theory along with a circuit representation of the probe plasma interaction.¹³ For the lower bound to this frequency range, we avoid any ion contributions to the total current as ions are unable to respond on the timescale of the electrons. For the upper bound, there will be no contribution from collisionless resistance (CR) (or resonance effects) covered in the original work in this series.¹¹ Then, unlike the case where a very low frequency is applied ($\omega < \omega_{pi}$, ω_{pe}), the ac current will have no contribution from the ions. This implies that the ac resistance is only a function of the change in electron current with applied ac voltage as seen in Eq (5). Without an ion response we are effectively including only the electron contribution to the I-V characteristic. Furthermore, at the plasma potential there is no sheath and from Eq. (4), $Re(Z_{ac}) \sim R_{ac}$. We then have at $V_p = \phi_p$,

$$\frac{dR_{ac}}{dV_p} = -R_{ac}^2 \left(\frac{d^2 I_e}{dV_p^2} \right) = 0 \quad (6)$$

and finally,

$$\left. \frac{d Re(Z_{ac})}{dV_p} \right|_{V_p = \phi_p} \simeq 0 \quad (7)$$

III.b Experimental Results

As seen above, variation of the probe's dc potential allows for the controlled change of the surrounding plasma sheath, which has measurable effects on the probe impedance. Varying the potential of the probe at a fixed frequency allows the plasma potential relative to the system ground potential to be determined, *i.e.*, it occurs at the local minimum expressed through Eq.(7). Figures (3) through (7) all show $Re(Z_{ac})$ for

multiple frequency sweeps versus applied probe bias for the three spheres under varying plasma conditions.

Figures (3) and (4) show data for the 25.4 mm radius probe under slightly varying plasma conditions. For Figure (3) the plasma potential determined in the usual fashion from Langmuir probe data, $\phi_p \sim 1.5$ V, plasma temperature, $T_e \sim 0.4$ eV and electron density, $n_e \sim 10^8$ cm⁻³. Plasma conditions did not vary substantially for Figure (4) data. Figures (5) and (6) show data for the 12.5 mm radius probe. The data of Figure (5) were taken for $\phi_p \sim 1$ V, $T_e \sim 0.9$ eV and $n_e \sim 4 \times 10^7$ cm⁻³. Figure (6) was taken with quite a bit of variation in plasma parameters during the data take. This is likely responsible for the variation in the position of the minimum and the absolute value of $Re(Z_{ac})$ at the minimum. For these data, $1 < \phi_p < 0.85$ V, $1.25 < T_e < 1.4$ eV and, $0.85 \times 10^8 < n_e < 1 \times 10^8$ cm⁻³. The final data set of Figure (7) was taken with the 9.5 mm radius probe. In this case there was also some variation in plasma parameters from beginning to end of the runs. For this case, $0.83 < \phi_p < 0.89$ V, $T_e \sim 0.8$ eV and, $7.8 \times 10^7 < n_e < 8.3 \times 10^7$ cm⁻³. In each case ϕ_p as found from the minimum is seen to be comparable to that obtained in the usual fashion from the probe IV sweep. It is also more reliable as the length of time the probe remains in the plasma can affect the conventional results due to contamination effects. These are ameliorated and in many cases here removed by continuous heating of the probe. Also to be noted from the figures is that although there are some variations in the position of the plasma potential as a function of frequency there is nevertheless always present a local minimum whose existence is independent of the frequency. So, for practical implementation only a plot of $Re(Z_{ac})$ vs V_{bias} is necessary to locate the local minimum. The energy distribution function and therefore the electron temperature can also be obtained from this analysis.

IV. Summary

We have presented a method of determining plasma potential using techniques developed over the past three years in studies of rf impedance probe techniques using very small amplitude signals compared to bias levels or typical plasma potential magnitudes. For this reason our technique is non-perturbative to the existing plasma and this is a significant departure from even conventional rf impedance probe studies. We are currently in the process of extracting the electron distribution function from data obtained in the plasma potential studies.

V. Figure Captions

Figure (1) – A photograph of the present NRL Space Physics Simulation Chamber showing magnetic field coils and two separate experimental areas separated by a large gate valve providing either experimental coupling between the two or isolation for separate experimentation. The results presented in this work were performed in the larger section surrounded by five magnetic field coils toward the rear of the photograph.

Figure (2) – A schematic representation of the Network Analyzer and coupling circuitry necessary for the swept frequency analyses of the spherical impedance probes. The Analyzer returns a representation of the signal reflected from the plasma and provides plasma complex impedance, The circuitry shown indicates both the application of the small non-perturbative analyzer signal in addition to the dc bias applied to the probes.

Figure (3) – A plot of the $Re(Z_{ac})$ for frequency scans varying from 11 to 20 MHz returned by the Network Analyzer vs applied bias voltage for the 25.4 mm radius sphere. For this run the plasma potential determined from Langmuir probe data, $\phi_p \sim 1.5$ V, plasma temperature, $T_e \sim 0.4$ eV and electron density, $n_e \sim 10^8$ cm⁻³.

Figure (4) – A plot of the $Re(Z_{ac})$ for frequency scans varying from 11 to 20 MHz returned by the Network Analyzer vs applied bias voltage for the 25.4 mm radius sphere. Plasma conditions did not vary substantially from those of Figure (3) above.

Figure (5) – A plot of the $Re(Z_{ac})$ for frequency scans varying from 1 to 8 MHz returned by the Network Analyzer vs applied bias voltage for the 12.5 mm radius sphere. For this run the plasma potential determined from Langmuir probe data $\phi_p \sim 1$ V, $T_e \sim 0.9$ eV and $n_e \sim 4 \times 10^7$ cm⁻³.

Figure (6) – A plot of the $Re(Z_{ac})$ for frequency scans varying from 7 to 13 MHz returned by the Network Analyzer vs applied bias voltage for the 12.5 mm radius sphere. There was quite a bit of variation in plasma parameters during the data take. This is likely responsible for the variation in the position of the minimum and the absolute value of $Re(Z_{ac})$ at the minimum. For these data, $1 < \phi_p < 0.85$ V, $1.25 < T_e < 1.4$ eV and, $0.85 \times 10^8 < n_e < 1 \times 10^8$ cm⁻³.

Figure (7) – A plot of the $Re(Z_{ac})$ for frequency scans varying from 4 to 20 MHz returned by the Network Analyzer vs applied bias voltage for the 9.5 mm radius sphere. The final data set was taken with the 9.5 mm radius probe. In this case there was also some variation in plasma parameters from beginning to end of the runs. For this case, $0.83 < \phi_p < 0.89$ V, $T_e \sim 0.8$ eV and, $7.8 \times 10^7 < n_e < 8.3 \times 10^7$ cm⁻³.

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VII. Figures

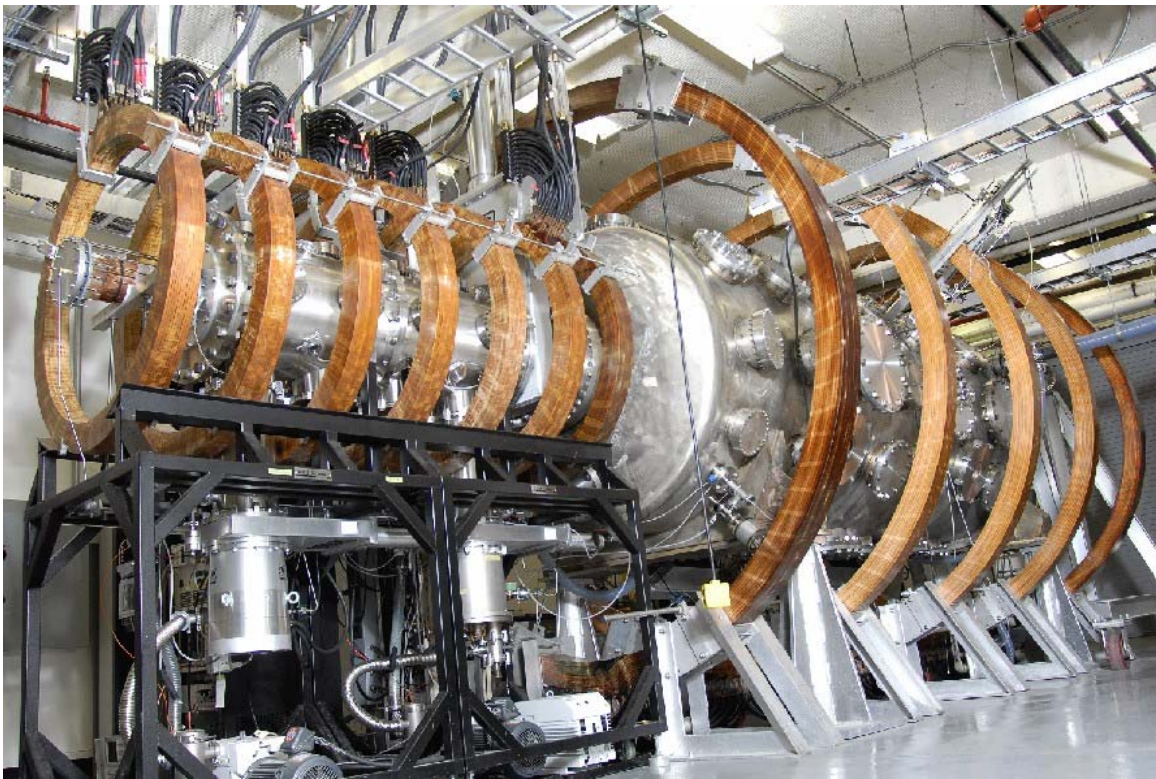


Figure 1

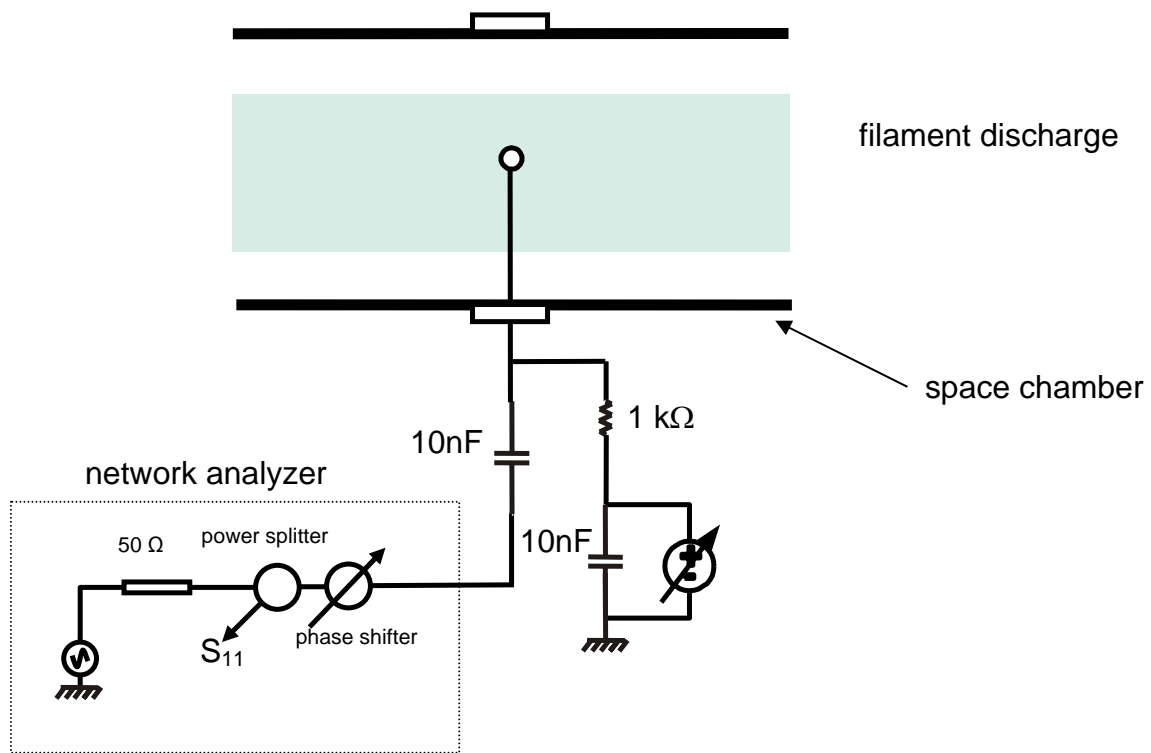


Figure 2

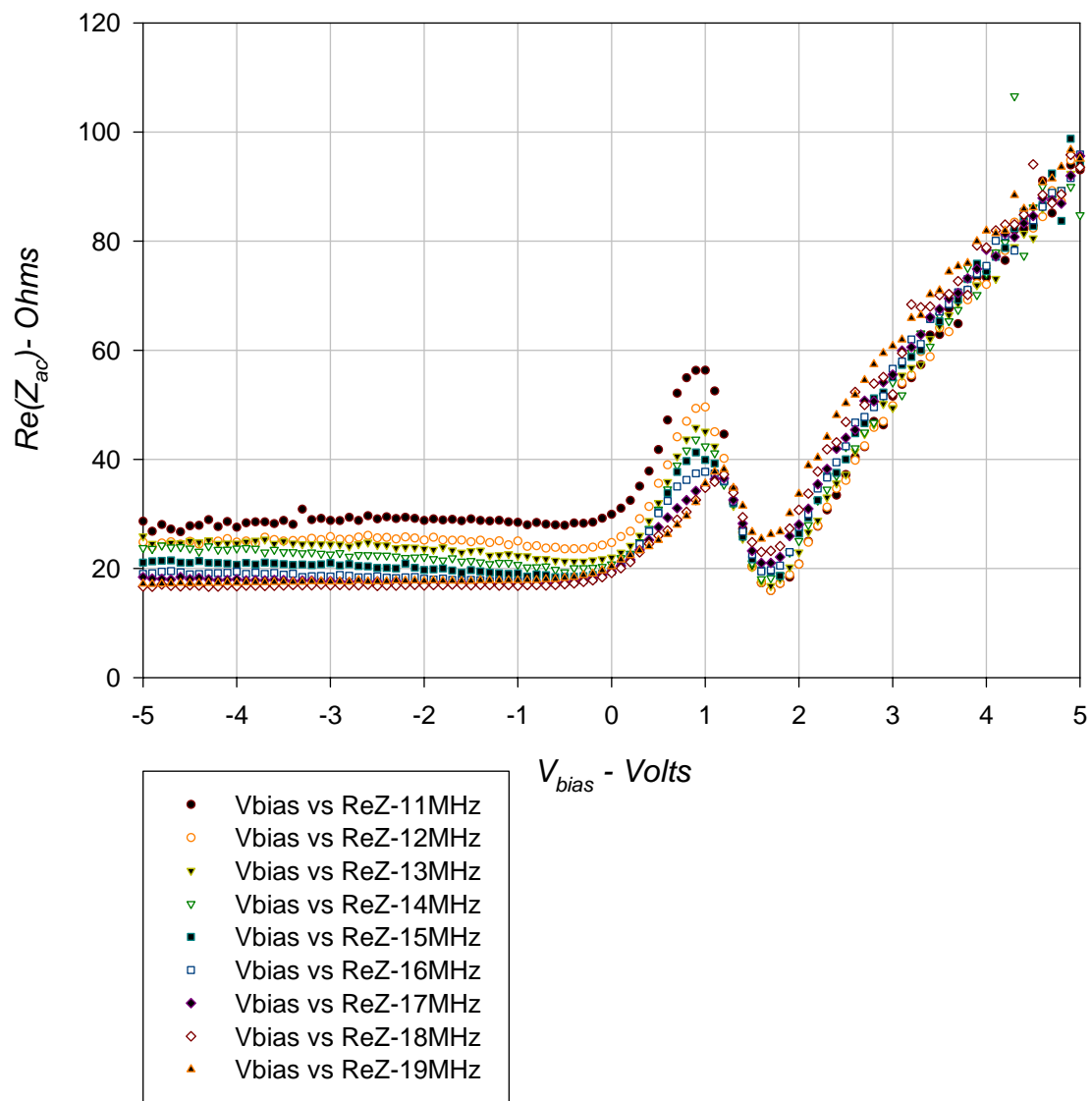


Figure 3

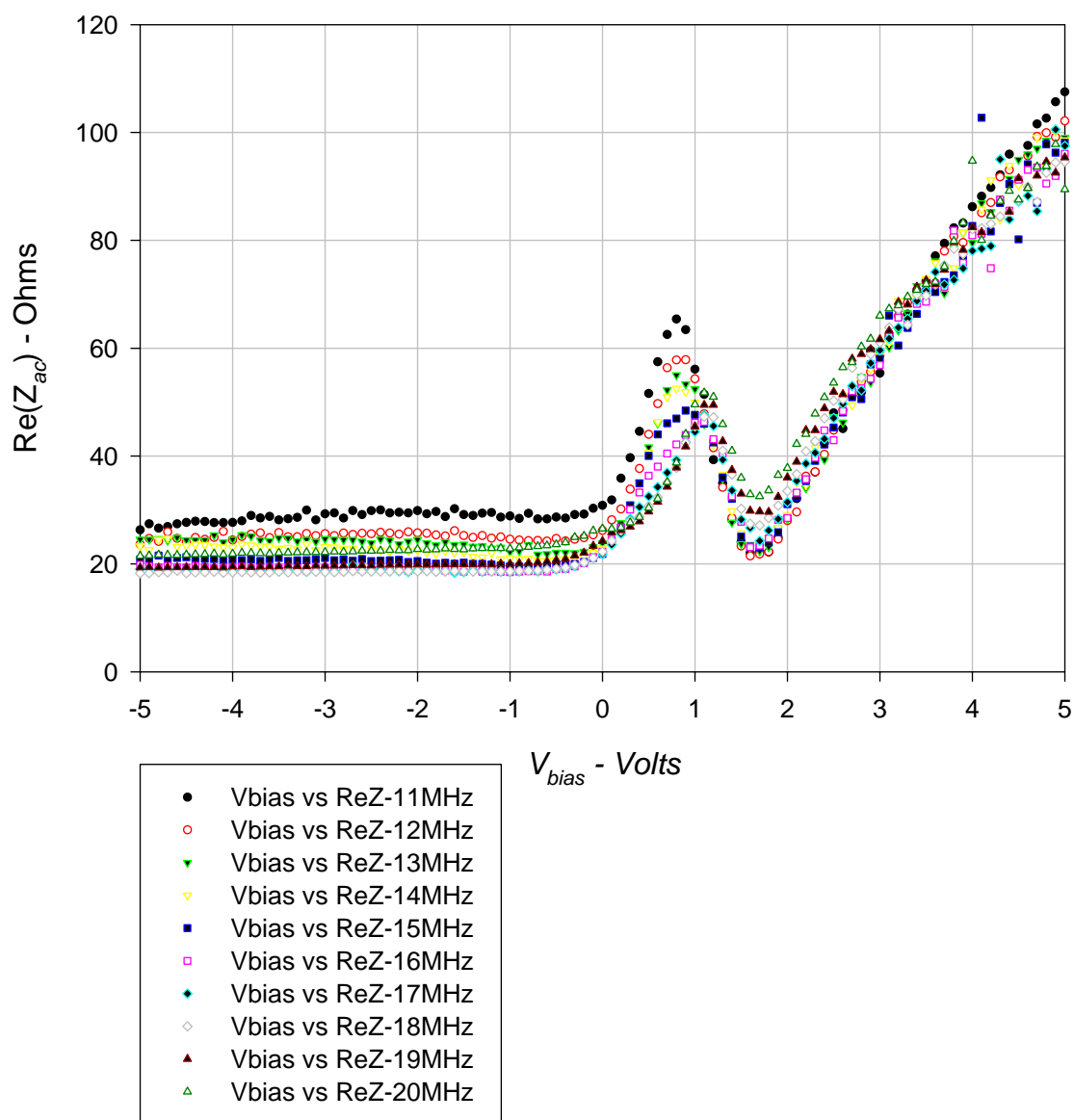


Figure 4

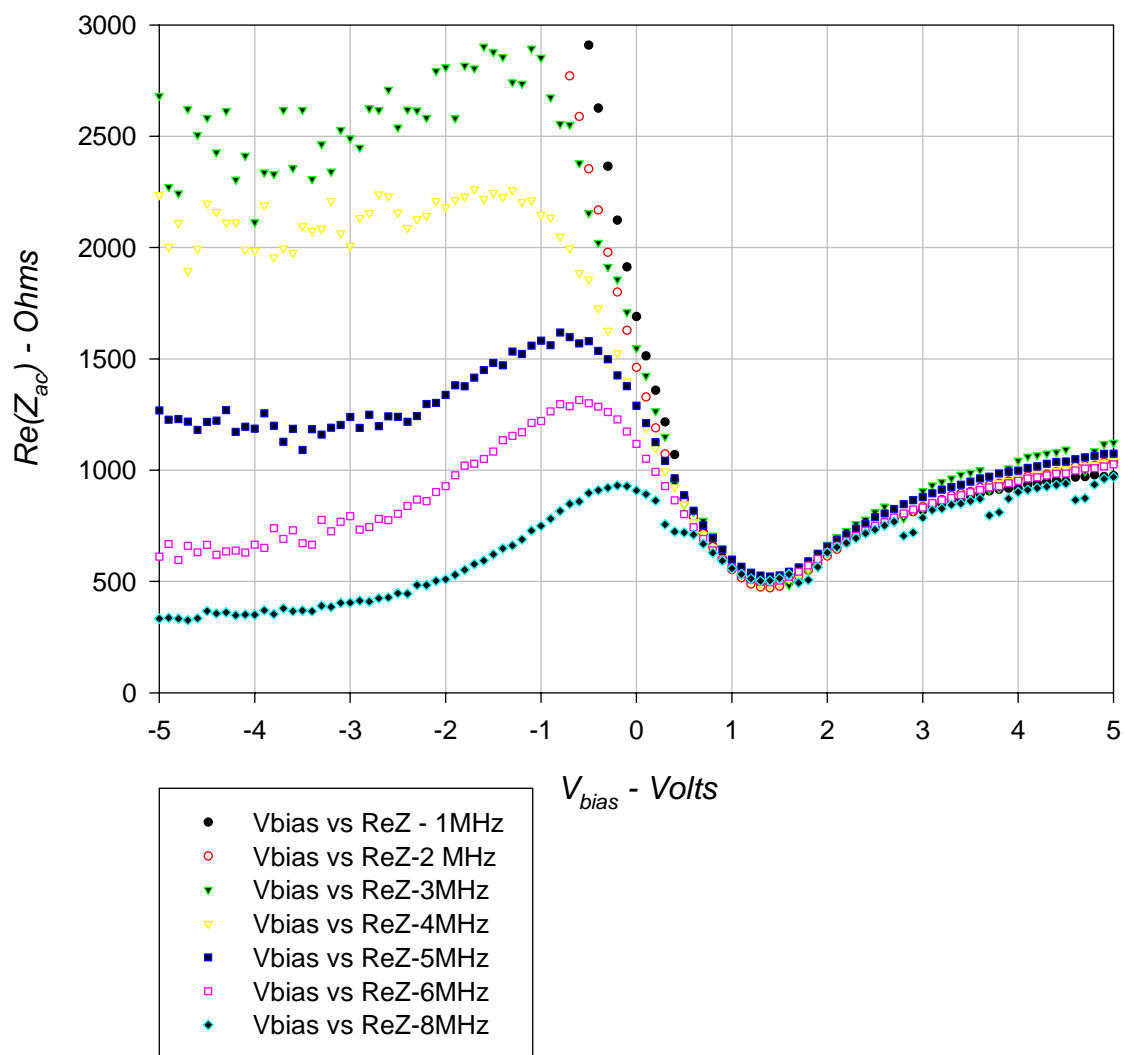


Figure 5

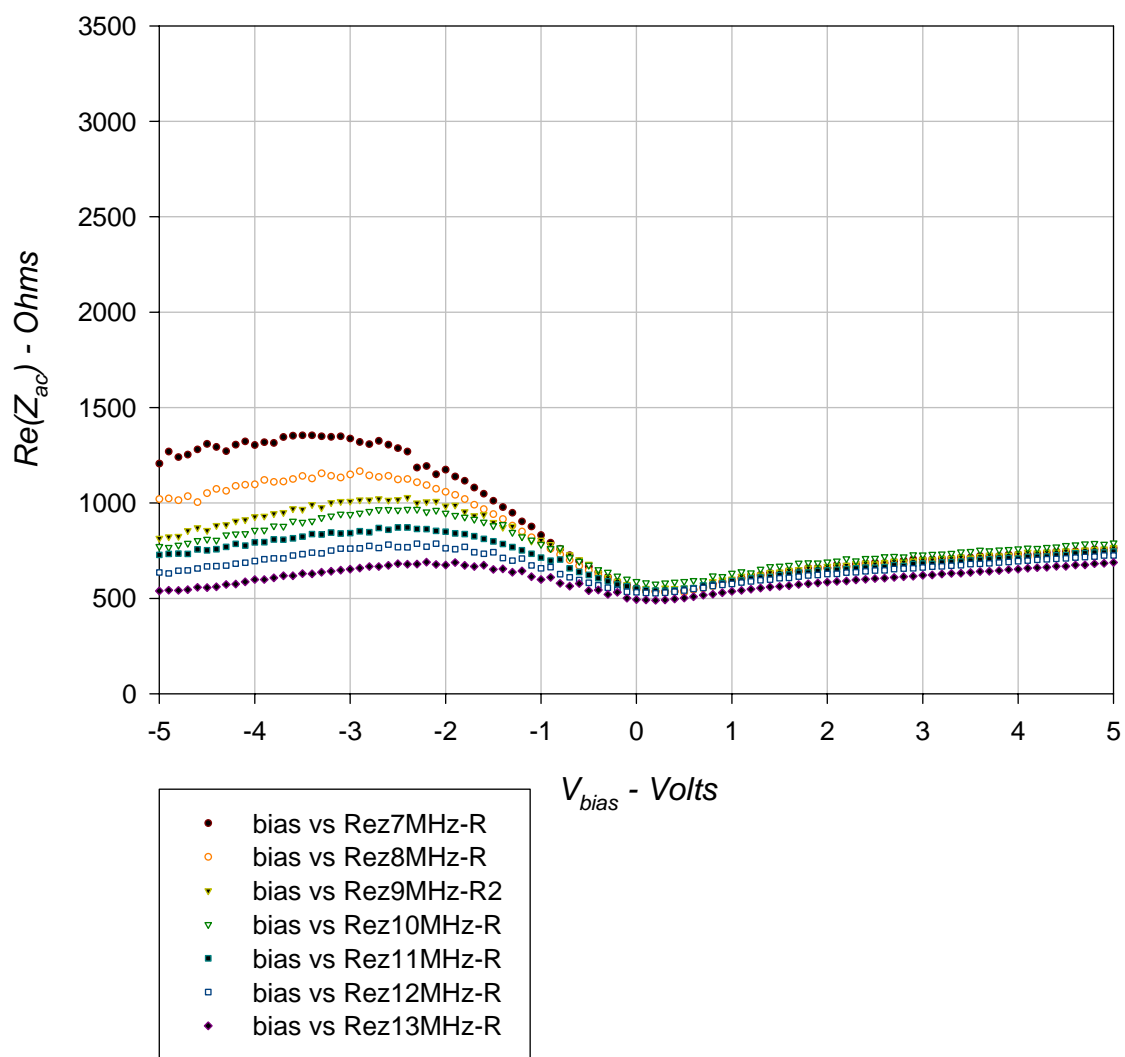


Figure 6

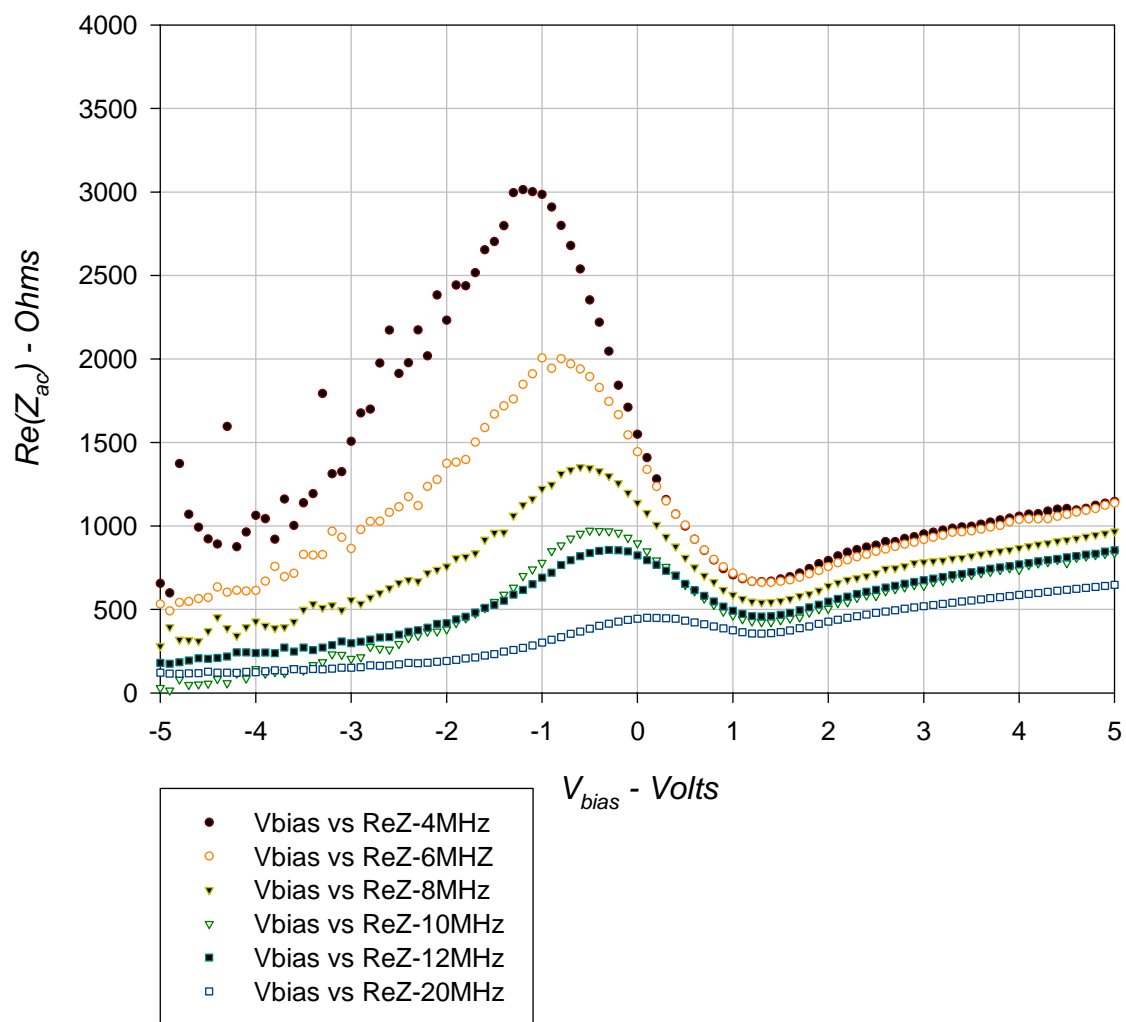


Figure 7

